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Exploring the Development of the Sciences

Georgia Irby
College of William and Mary, glirby@wm.edu

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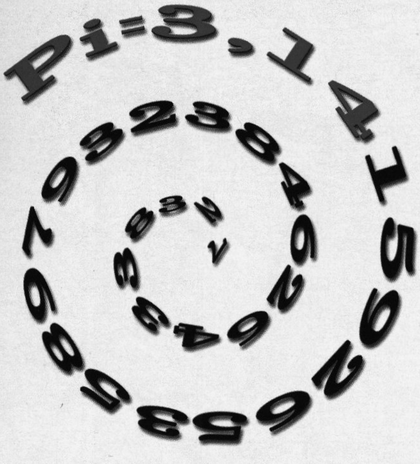
EXPLORING THE DEVELOPMENT OF THE SCIENCES

AUTODIDACTS, POLYMATHS, AND THEIR THEORIES

Humankind has always sought to understand the natural world and unravel its mysteries. From the beginnings of recorded literature, scientists (people of knowledge, from the Latin verb *sciō*, "I know") have asked of what is the world made, how are things related to each other, what is the relative size of the earth to celestial bodies, what is the arrangement of the cosmos (universe), and how does humankind fit into the cosmos. The Greek poet Hesiod (around 700 BCE) tried to explain earthquakes as resulting from the anger of the Greek god of the sea, Poseidon, who thrust his trident into the earth when angry. Thales (around 600 BCE) was the first Greek who tried to explain the world on the basis of the properties of natural substances. Thales believed that everything derived from water and that the properties of water explained why things happened. For example, Thales suggested that the earth was a flat disc floating on a cosmic sea. Consequently, ripples in the sea jolted the earth, resulting in earthquakes. Early Greek scientists believed that every event could be explained rationally on the basis of scientific causes.

Greek and Roman thinkers were often autodidacts (self-taught, from the Greek pronoun *autos*, "self, oneself," and the verb *didaskō*, "I teach") and invariably polymaths (people who know many things, from the Greek adjective *polus*, "much," and verb *manthanō*, "I learn, know") with broad interests and knowledge. Aristotle (384–322 BCE), the famous tutor of Alexander the Great, wrote books in Greek on almost every topic of human knowledge except mathematics. Aristotle studied and lectured on astronomy, biology, physics, literary criticism, ethics, politics, and rhetoric. In gratitude for his education, Alexander, himself a polymath, sent biological specimens from his campaigns back to his mentor in Greece. Archimedes (287–212 BCE) made important discoveries in many scientific fields, including theoretical mathematics (especially in

Greece's ten drachma coin minted in 1990 celebrates the famous philosopher Aristotle. With its membership in the European Union, Greece, like the other member nations, began to mint Euro coins in 2002. Such coins bear images of significance to the country circulating them.



Around 250 BCE, Archimedes calculated the ratio of a circle's circumference to its diameter. An earlier Egyptian document dated to 1650 BCE gives a value of 3.1605. Archimedes's value, however, was not only more accurate, it was the first theoretical, rather than measured, calculation of π.

measuring the surface area and volume of curved objects like spirals and in calculating extremely large numbers such as the number of grains of sand required to fill up the universe), mechanics (properties of simple machines such as levers), optics (the apparent size of the sun), and hydrostatics (the nature of liquids). The story about Archimedes running naked through the streets and shouting *Eureka* (Greek for "I have discovered it!") after discovering the theory of specific density (the ratio between an object's mass and its volume) is probably just an urban myth.

Ancient Greek scientists would consider our own modern approach of narrow specializations and the strict divisions of scientific fields artificial and unhelpful. Strabo (63/62 BCE–24 CE), a Greek historian who wrote an extensive geography of the *oikoumene* (from the Greek verb *oikeō*, "I dwell, inhabit"; compare the Greek noun *oikos* "home," and verb *oikonomeō* "I manage a household," from which the English word "economy" derives), says "wide learning, which alone makes it possible to undertake a work on geography, is possessed solely by the man who has investigated things both human and divine—knowledge of which, they say, constitutes philosophy. And so, too, the utility of geography—and its utility is manifold, not only as regards the activities of statesmen and commanders but also as regards knowledge both of the heavens and of things on land and sea, animals, plants, fruits, and everything else to be seen in various regions—the utility of geography, I say, presupposes in the geographer the same philosopher, the man who busies himself with the investigation of the art of life, that is, of happiness" (Strabo, *Geography* 1.1.1). In other words, all knowledge is interconnected, and a true understanding of one discipline (geography) cannot be attained in ignorance of others (philosophy or zoology).

The Roman architect Vitruvius relates the legend of Archimedes whom King Hieron II of Syracuse had asked to ascertain without inflicting damage whether his crown was actually made from pure gold. As Archimedes watched the water spill from the tub as he stepped in, he realized how he could answer the king's query.

Although Greek science continued to advance steadily from Thales to Aristotle, a real scientific boom occurred after Alexander the Great.

Alexander the Great astride Bucephalus leads his troops with their characteristic Greek helmets against an eastern army identified by their dress and their "orientalized" eyes. The profile of the youthful Alexander is an image replicated on ancient coins. Alexander was a lifelong student who learned from the lands and peoples he conquered.

Alexander himself helped to advance Greek science through gathering all sorts of information on his campaigns and by establishing contacts with different cultures of diverse approaches to science. But the golden age of Greek science occurred a little later at Alexandria in Egypt, where the son of one of Alexander's generals founded the famous *Mūsēum*, a center of learning. The *Mūsēum* served as a central meeting place for people of knowledge to discuss and exchange their ideas. At the *Mūsēum*, Archimedes advanced the science of hydrostatics; Aristarchus (around 280 BCE) proposed a theory of heliocentrism; Herophilus (330–260 BCE) pioneered the study of human anatomy by performing human dissection; and Hipparchus (190–120 BCE) discovered the precession of the equinoxes (as if at the edges of a very slowly spinning toy top, the stars appear to shift over the centuries as they rise in the night sky at particular times of the year). The Library attached to the school quickly housed the largest collection of manuscripts, including classic works of Greek literature, science, bibliographic surveys, commentaries (especially on the *Iliad* and *Odyssey*), and Greek translations of important works in other languages including the Jewish Septuagint (Old Testament). Customs officials at the port of Alexandria were under strict orders to confiscate any manuscripts brought into the city by travelers. The originals were usually deposited in the Library, and copies were then delivered only to the luckiest book owners.

Eratosthenes served as the director of the *Mūsēum* for forty years (around 245–205 BCE). A polymath who lived in a time of intellectual giants (e.g., Archimedes), he earned the rather unkind nicknames "Beta" ("second best," from the second letter of the Greek alphabet, *beta*), and "Pentathlos" (an all around athlete, good enough to win only at three out of five set competitions at the Olympics: from the Greek adjective *pente*, "five," and noun *athlos*, "contest"); that is to say, Eratosthenes was a "jack-of-all-trades." Born in Cyrene (modern-day Libya), Eratosthenes studied philosophy and mathematics in Athens, a city whose reputation as an academic center remained strong throughout antiquity. Eratosthenes came to Alexandria to direct the *Mūsēum* and to tutor the king's son, Ptolemy Philopater (born around 245 BCE). As head librarian of the *Mūsēum*, Eratosthenes, who was deeply interested in all aspects of human knowledge, wrote on chronology, mythology, grammar, literary criticism, astronomy, harmonics, and geography. He also wrote poetry.

Eratosthenes is most famous for estimating the circumference of the earth. To estimate the earth's circumference, Eratosthenes used astral data together with a simple and elegant ratio, based on the geometry of the sphere. He made three simple assumptions: that the earth was a perfect sphere; that the sun was sufficiently far enough away from the earth that its rays were parallel when striking the earth; and that two Egyptian cities from which he made his calculations, Syene (Aswan) and Alexandria, lay on the same meridian (Alexandria is actually 3° west of Syene). Eratosthenes compared readings from these two cities on the same day, the summer solstice, at high noon. At Syene no shadows were cast at midday because the sun was precisely at its zenith, but a slight shadow was cast at Alexandria, because of the curvature of the earth and the fact that Alexandria is north of Syene. He then measured the angle of the shadow cast at Alexandria as one-fiftieth of a circle, and he knew that the distance between Syene and Alexandria was approximately 5,000 *stadia* (a *stadion* is the Greek unit of distance, equal to 600 Greek feet, but varies from place

In the lower right quadrant of this photograph of the stadium at Olympia one can see the white starting blocks that run across the field. The stone wall by the edge of the grassy knoll is the entrance through which the athletes entered the running field. Spectators sat on the banks along the running area.

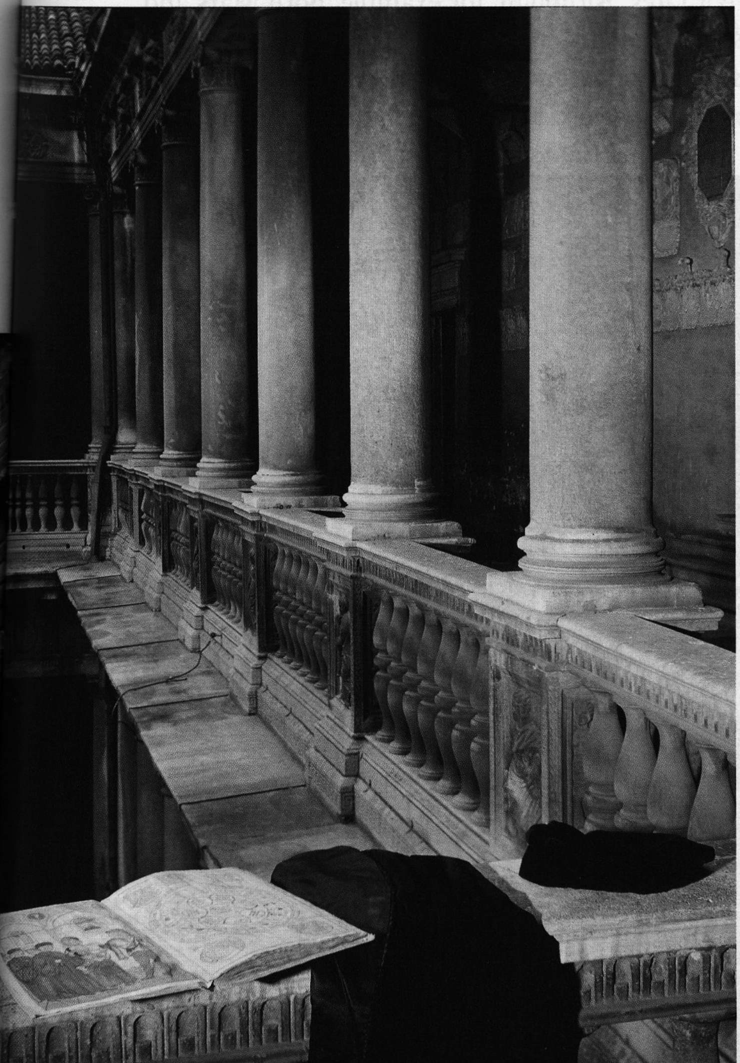
to place: the *stadion* at Olympia was 632.5 feet, the length of the stadium there; the Athenian *stadion* measured 606.9 feet, the Egyptian *stadion* was 516.7 feet). Eratosthenes multiplied 5,000 *stadia* (the length of the arc between Syene and Alexandria) by 50 (the number of units in his circle) to find the earth's circumference: 250,000 *stadia* (24,412.5 miles; we assume that Eratosthenes employed the Egyptian *stadion*). This value is remarkably close to our own estimate of 24,901 miles. Eratosthenes later adjusted his estimate to 252,000 (24,608 miles), a number divisible by 60, and even closer to modern calculations. Unfortunately, many of his successors rejected the estimate because Eratosthenes was not recognized as an important mathematician. Instead, the "orthodox" estimate of the earth's circumference was calculated by the mathematician Poseidonius (around 100 BCE) as 180,000 *stadia* (between 17,615 and 21,564 miles, depending on which *stadion* Poseidonius used). Poseidonius's value, considerably smaller than that of Eratosthenes, was accepted by the Greek astronomer and mathematician Ptolemy (second century CE), whose geocentric arrangement of the cosmos was accepted without question until the ninth century when a Muslim astronomer, Ibn al-Haytham, noticed numerous errors and scathingly attacked Ptolemy's astronomical system as "utterly impossible." Columbus, incidentally, bowing to the authority of Ptolemy, also accepted the smaller value and, hence, assumed that he made landfall in China, when he actually fell short by some 7,000 miles, landing instead somewhere in the Bahamas.

Most science in antiquity was written in Greek. A shift occured in the Middle Ages when Latin became the common language of communication, the *lingua franca* of philosophers and the universities. Although Copernicus wrote in Latin, his approach to science had more similarities than differences from his Greco-Roman predecessors. Like Greek and Roman scientists before, Nicolaus Copernicus (1473–1543) was a man of great genius and deep intellectual curiosity. At the University of Cracow, Poland, while training for the priesthood, Copernicus also took classes

The Jagiellonian University in Cracow was established in 1364. The *Collegium Maius* is a fine example of fifteenth-century Gothic architecture: its inner courtyard is surrounded by arcades and features a staircase leading from the ground floor with its lecture rooms to the first floor halls for official ceremonies.

in mathematics, astronomy, and astrology, which at the time was considered a rigorous branch of mathematical astronomy. Before earning a degree from the University of Cracow, he moved to Bologna in northern Italy to study Canon Law of the Roman Catholic Church. At Bologna, Copernicus continued to study mathematics and astronomy, and there he learned Greek, a language which was not commonly taught at universities in the fifteenth century. Knowing Greek was important to a budding astronomer since the works of Ptolemy and other great astronomers from antiquity were written in Greek and had not been translated into Latin. Copernicus was able to analyze directly the ancient Greek astronomical observations which were at best poorly understood by his colleagues. Like Eratosthenes at the *Mūsēum*, Copernicus was lucky enough to have the access to resources that helped him develop his own theories: knowledge of Greek and friendship with Bologna astronomy professor Domenico Maria Novara, one of the few who dared to question the authority of Ptolemy. Furthermore, Copernicus consulted Arabic scholars including the Muslim mathematician and astronomer al-Battani (around 858–929) whose *Dē mōtū stellārum* (*Kitab al-Zij*) was translated into Latin in 1116, and Greek scientific treatises which were translated into Arabic and then into Latin, before the original Greek texts were lost. Copernicus also studied medicine at Padua where the medical curriculum included an emphasis on astrology in medical diagnosis and treatment; this branch of astrology, called iatro-astrology (from the Greek noun *iatreia*,"healing"), dated back to antiquity when it was believed that the stars and other heavenly bodies could have a real effect on the lives of people on earth. Copernicus finally earned a doctorate in Canon Law from the University of Ferrara, also in northern Italy, in 1503.

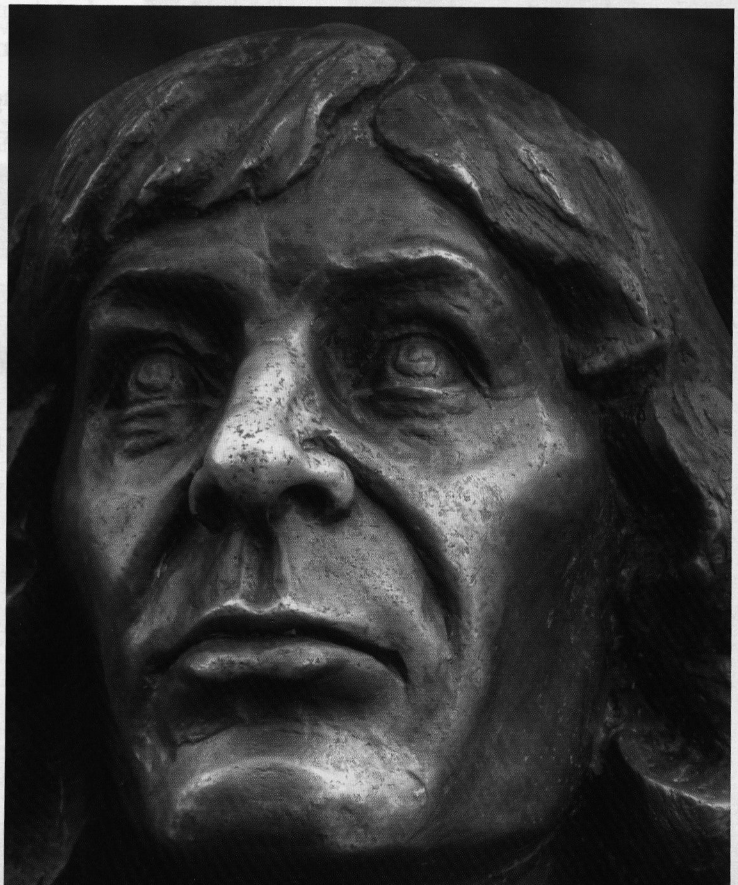
Through his official career as a Church administrator, Copernicus helped to stabilize eastern European currency, offered political advice in wartime, and was a consulting physician for Prussian nobles (southeast Baltic coast). Nonetheless, fascinated by astronomy, he made astronomical observations when he could: as a Church official, his responsibilities were pressing, and the frequent fog at Frombork in northern Poland, where Copernicus lived his adult life and where he had a roofless tower to observe the heavens, was not conducive to astronomical observation.



Founded in 1222, the University of Padua boasted one of the finest medical schools on the continent. Copernicus studied medicine at Padua in 1501. One can visit the anatomy theatre where he attended classes as did Andreas Vesalius. One can also see the podium from which lectures were given.

Copernicus is most famous for the theory of heliocentrism, first suggested by Aristarchus, but rejected in antiquity because of the lack of visible stellar parallax (the apparent displacement of stationary objects resulting when the observer moves). Copernicus described his system first in *Dē hypothesibus mōtuum caelestium ā sē cōnstitūtīs commentāriolus* (*Commentāriolus*) and later published a more developed explanation in *Dē revolūtiōnibus orbium caelestium.*

Copernicus analyzed astronomical observations at Cracow and Frombork (which he assumed was on the same meridian with Cracow, but is actually ¼° west) using the same type of data, records of lunar and solar eclipses, that Eratosthenes and other Greeks had used to calculate the latitudes of different places. Copernicus suggested that the earth was not the center of the universe, but rather that the earth (and the other planets) revolved around the sun. He argued that the earth only seemed not to move, and that the apparent daily rotation of the heavens, in fact, results from the real daily rotation of the earth on its axis (diurnal axial rotation had first been proposed by the Greek astronomer Heracleides, born 387 BCE). Furthermore, the apparent journey of the sun through the constellation of the zodiac results from the earth's real annual revolution around the sun, and the apparent retrograde motion of the planets (occurring when planets, usually moving from west to east in the night sky, seem to move westward for a short time and then to resume their eastward trajectory) results from the fact that the planets, including the earth, revolve around the sun at different rates. Although, for example, both Mars and Earth revolve around the sun in the same direction, Earth, which is closer to the sun, takes less time to make a complete circuit. When Earth is "behind" Mars, Mars seems to travel eastward; but when Earth "overtakes" Mars, Mars seems to move "backward" or westward.



This image of Copernicus is from a statue at the castle of Olsztyn, Poland. While living in the castle, Copernicus made observations of the movement of the planets and included these findings in his life's work *Dē revolūtiōnibus orbium caelestium.* He wrote the first chapter of that work while at the castle.

Copernicus countered the ancient arguments against Aristarchus's theory of heliocentrism by suggesting that the universe was so large and the stars were so far away that any stellar parallax would be undetectable to the naked eye. Copernicus was also able to reconcile heliocentrism with Aristotle's definition of natural motion and doctrine of natural place: celestial bodies move in perpetual circles; terrestrial bodies move in straight lines, stopping when they reach their natural places, "sinking of their own weight." Any other motion, according to Aristotle, is "violent." Copernicus recategorized the earth as a celestial body (hence it could move circularly), but conceded that displaced parts of the earth (rocks, tree branches, etc.) are subjected to "violent motion." Centuries earlier, Ptolemy had objected to the idea of the earth's axial rotation. He argued that terrestrial axial rotation, a violent motion, would result in the earth bursting apart and dropping out of the sky, in the shaking up of loose objects on the ground, and in clouds constantly floating away westward. Copernicus answered, "Ptolemy has no cause to fear that the earth and everything earthly will be disrupted by a rotation" because such an earth, constantly threatened by violent motion, would simply not last long and the system "brought into existence by nature is well ordered and well preserved in its best state" (Copernicus, *Dē revolūtiōnibus* 1.8). Furthermore, Copernicus argued, the air and water on the earth "conform to the same nature (i.e., same rules of physics) as the earth" because of their proximity to the earth, and so clouds and lakes rotate eternally with the earth. Copernicus accepted the ancient theory that the earth was tilted on its axis to explain the varying length of days and the precession of the equinoxes.

Heliocentrism seemed to contradict the Bible, and Copernicus proceeded cautiously. He published *Commentāriolus* anonymously and agreed to publish *Dē revolūtiōnibus* only after his friend Georg Joachim Rheticus, a mathematician, astronomer, and Lutheran minister, published *Nārrātiō prīma* (1540), a sort of book review of *Dē revolūtiōnibus*. *Nārrātiō prīma* did not attract a great deal of controversy, so Copernicus wrote a dedication to the reigning pope, Paul III (*regnat* 1534–1549), and added a preface in which he declared *mathēmata mathēmaticīs scrībuntur* (Greek astronomers called themselves *mathēmaticī*), which is to say that Copernicus believed in a separation of church and science. The publisher, Andrew Osiander (1498–1552), however, disagreed with the book's potentially controversial content. Osiander anonymously appended another preface asserting that *Dē revolūtiōnibus* was not a true account of the universe but more of a thought experiment. Rheticus and others protested Osiander's contradictory disclaimer, and Rheticus even crossed out the preface in his own copy.

Nonetheless, probably because of Osiander's preface, the book did not attract as much controversy as it could have. Although most clergy and even some astronomers (including the brilliant Tycho Brahe: 1546–1601) rejected Copernicus's system, the Polish astronomer was highly admired, and his theory was selectively accepted. Nor did the Church render an official stand on Copernicus's system, much less declare it a heresy. Eventually, Copernicus's theory was accepted as sound. In fact, Copernicus's estimates for the distances of the planets from the sun are remarkably close to modern values. Galileo Galilei (1564–1642) promoted Copernicus's theory, leading to official Church condemnation of Copernicus's *Dē revolūtiōnibus* and charges of heresy against Galileo. In the Protestant Netherlands, Johannes Kepler (1571–1630), who also improved the design for the newly developed refracting telescope, advanced Copernicus's work to develop an even more accurate description of the solar system.

Kepler, who had moved frequently in the course of his career, sometimes because his religious beliefs conflicted with those of his patrons, spent the last years of his life in Regensburg, Germany, the cultural capital of southern Germany. Regensburg paid tribute to this famous resident with the Kepler Memorial.

Although modern professional scientists tend to specialize in very narrow fields, they continue to explore broad interests. For example, Albert Einstein (1879–1955), best known for the theories of general and special relativity, was also an outspoken critic of Nazi Germany, wrote philosophical books about Zionism and pacifism, was interested in cosmology (how the universe came into existence, a guiding question of early Greek astronomy), and played the violin.

Richard Feynman (1911–1988), a quantum physicist who contributed to the atomic bomb theory and worked on the "Manhattan Project" (the joint venture between the United States, United Kingdom, and Canada to develop nuclear weapons during World War II), was also an expert safe cracker and a noted practical joker, and he deciphered Mayan hieroglyphics. Isaac Asimov (1920–1992), best known as a writer of science fiction, studied and taught biochemistry but wrote widely on everything from commentaries on the Bible and Shakespeare to treatises on theoretical physics. Astronomer and cosmologist Carl Sagan (1934–1996) was a political activist, successful popularizer of theoretical astronomy (*Cosmos* was filmed for PBS), and a novelist. The paleontologist and evolutionary biologist Stephen Jay Gould (1941–2002) also wrote broadly on the history of science as it connects to all branches of human knowledge, and he even played himself on *The Simpsons*.

Like his fellow modern scientists and like his Greek and Renaissance predecessors, Stephen Hawking (1942–) pursues broad scientific interests in mathematics, thermodynamics, relativity, quantum mechanics, astronomy, and cosmology. His works of popular science are lucid and full of humor (he claims to have sold more books on physics than Madonna has on sex). Not taking his own genius too seriously, he has even played himself on *Red Dwarf*, *Star Trek: The Next Generation*, and several episodes of *The Simpsons* and *Futurama*.

In the late twentieth and early twenty-first centuries, we come full circle, back to the foundations of Greek scientific inquiry. Hawking is asking the very same questions that the earliest Greek scientists had asked: what is the world (the universe) made of; what are its parts; how do these parts fit and work together; how did the universe come to be; and what factors will determine the universe's passing away. Although the past millennia have seen countless changes in scientific approaches, philosophy, tools, and even the sheer scope of human imagination, the human quest for knowledge remains eternal and perpetual, like Aristotelian celestial motion. Just as Thales had proposed a unified theory of physics based on the properties of water, Hawking seeks to develop a unified theory of physics that will describe everything that occurs in the universe. Together with other scientists, Hawking is working to combine Einstein's general theory of relativity with the uncertainty principle, a random element of quantum theory espoused by Niels Bohr (1885–1962), and with Feynman's notion that the universe has multiple histories, each with its own probability rating. For example, Einstein's general theory of relativity suggests that the universe has a beginning and that the universe began with a "Big Bang." But Einstein's theory fails to account for all events especially those further back in time, closer to the moment of the "Big Bang," perhaps because he had not taken into account the uncertainty principle. Einstein famously declared that "God does not play dice." Hawking, however, suggests that "God is quite

This lifelike statue of Einstein depicts him as one might find him in a park when he lived in Princeton, New Jersey. The sculpture in the Science Park of Granada, Spain, invites one to sit and join the genius on the bench. The open air museum offers a variety of hands-on science-related activities.

a gambler," and he compares the universe to a casino with dice being rolled on every occasion. In our large and expanding universe, the number of rolls of the dice is very high and the results average out to something mathematically predictable. But when the universe is small (since the universe is expanding, it must have once been tiny), the number of rolls of the dice is few, the results are less predictable, and the uncertainty principle becomes important.

Like Eratosthenes who not only estimated the earth's circumference but also mapped the *oikoumene*, Hawking seeks to explain the relationship between events (if not places) in the universe. Like Copernicus who remapped the solar system in developing a unified theory of astronomy that explained all the events that we can see in the night sky, Hawking attempts to understand various deep space phenomena, such as the conversion of matter into energy in black holes (regions in space-time with gravity so strong nothing can escape) and the radiation of energy from black holes, the existence of wormholes (thin tubes of space-time connecting distant regions of space) and their ramifications for travel in space and time. Although time has uncovered flaws in every scientific idea from the Greeks onward, and although Hawking admits that his own questions may be unanswerable (at least during this century), he speaks for all scientists from Thales to himself when he says, "We must try to understand the beginning of the universe on the basis of science. It may be a task beyond our powers, but we should at least make the attempt" (Stephen Hawking, *The Universe in a Nutshell* [2001] 79).

Georgia Irby-Massie
Assistant Professor of Classics
The College of William and Mary
Williamsburg, Virginia